Respray Requests on Custom-Applied, Glyphosate-Resistant Soybeans in Illinois: How Many and Why

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If an herbicide application fails to control a targeted weed community sufficiently, farmers may try to eliminate surviving weeds with a follow-up application (hereafter "respray"). Despite the implications of resprays on the spread of herbicide-resistant weeds, respray frequencies and causal factors are poorly understood. A two-part survey of glyphosate-resistant soybean fields and custom application services was conducted in Illinois during 2005 and 2006 to determine the relative frequency of respray requests for postemergence glyphosate, and to identify weed community factors associated with glyphosate respray requests. A meta-analysis was then utilized to project the impacts of weed community factors driving respray requests on crop yield. Glyphosate resprays were requested for 14% of surveyed fields in both 2005 ($n = 43$) and 2006 ($n = 90$). In 2005, respray requests were highly associated with both population densities of weed communities visible from roadsides and incidences of skips (i.e., rectangular areas of escaped weeds indicating custom application failure). A skip increased the odds of respray request by more than ninefold, and population densities of weed communities visible from roadsides were, on average, 2.5 times greater in respray-requested fields compared with nonrequested fields. In 2006, respray requests were associated with population densities of weed communities identified by walking through fields. Contrary to 2005, requests in 2006 were concentrated in those fields with low weed population densities. Prior to resprays, weed communities capable of causing substantial soybean yield loss were present in both respray-requested and nonrequested fields in 2005 but in only nonrequested fields in 2006. Although this investigation indicated that custom applicators can take actions to reduce respray requests (i.e., avoiding skips), farmers and custom applicators should be prepared to implement additional weed control after postemergence glyphosate applications because damaging weed communities may remain.

Nomenclature: Glyphosate; soybean, *Glycine max* (L.) Merr.

Key words: Herbicide reapplication, custom application, soybean weed control, farmer decision making, herbicide resistance management.

Si la aplicación de un herbicida no funciona para controlar suficientemente una comunidad de malezas específica, los agricultores quizás traten de eliminar las malezas sobrevivientes con una aplicación subsecuente (de ahora en adelante re-aplicación). A pesar de las implicaciones de la re-aplicación en la propagación de malezas resistentes al herbicida, las frecuencias de las aplicaciones y de sus factores causales son poco comprendidos. Una encuesta de dos partes de cultivos resistentes al glifosato y de los servicios de aplicación personalizada fue llevada al cabo en Illinois durante 2005 y 2006 para: (1) Determinar la frecuencia relativa de solicitudes de re-aplicación para el glifosato post-emergente y (2) identificar los factores de las comunidades de malezas asociados con las solicitudes de re-aplicación de glifosato. Después, se utilizó un meta-análisis para proyectar los impactos en el rendimiento del cultivo de los factores de la comunidad de malezas que incentivaran las solicitudes de re-aplicación. Las re-aplicaciones de glifosato se solicitaron para el 14% de los campos encuestados tanto en 2005 ($n = 43$) como en 2006 ($n = 90$). En el 2005 las solicitudes de re-aplicación se relacionaron en alto grado tanto con las densidades de población de las comunidades de malezas visibles desde la orilla de los caminos como con existencia de "manchones" (o sea áreas rectangulares de malezas que no fueron alcanzadas por la primera aplicación del herbicida). Uno de estos "manchones" incrementó más de 9 veces las probabilidades de que hubiera una solicitud de re-aplicación y en promedio las densidades de población de las comunidades de malezas visibles desde la orilla de los caminos fueron 2.5 veces mayores en campos donde se solicitó la re-aplicación, comparados con los que no la solicitaron. En 2006, las solicitudes de re-aplicación fueron relacionadas con las densidades de población de las comunidades de malezas que fueron identificadas caminando a través de los campos. Contrario al 2005, las solicitudes en 2006 se concentraron en campos con bajas densidades de población de malezas. Anterior a las re-aplicaciones, se encontraron en 2005 comunidades de malezas capaces de causar una pérdida sustancial en el rendimiento de la soya, tanto en campos que solicitaron la re-aplicación como los que no. Sin embargo, en 2006 dichas comunidades solamente estuvieron presentes en los campos donde no se solicitó. Aunque esta encuesta indicó que los aplicadores de herbicidas pueden tomar acciones para reducir las solicitudes de re-aplicación (o sea, evitando los "manchones"), los agricultores y los aplicadores de herbicidas deben estar preparados para implementar controles adicionales de malezas posteriores a las aplicaciones post-emergentes de glifosato ya que algunas comunidades de malezas dañinas pueden persistir.

Glyphosate is an integral component of soybean production in Illinois, as up to 90% of annual soybean hectares in this state (approximately 3.8×10^6 ha) are planted with genetically engineered, glyphosate-resistant varieties (U.S. Department of Agriculture–National Agricultural Statistics Service [USDA-NASS] 2009). Although widely used at

present, the future for glyphosate in soybean production in Illinois is uncertain as weed species, including horseweed (*Conyza canadensis* [L.] Cronq.) and common waterhemp (*Amaranthus rudis* Sauer), have developed resistance to label rates of glyphosate (Heap 2009). To help preserve glyphosate's utility in soybean production, knowledge of the commercial production practices that contribute to the spread of glyphosate resistance in weed communities is urgently needed.

Approximately 45% of herbicide applications to soybean fields across Illinois are administered by contracted application services (hereafter "custom applicators") (U.S. Department of Agriculture–North Central Integrated Pest Management Center [USDA-NCIPMC 2000]), and up to 65% of soybean farmers in Illinois hire custom applicators (Czapar et al. 1995). Accordingly, chemical weed control practices across Illinois are greatly influenced by the exchange of information between custom applicators and farmers. Typically, farmers and custom applicators develop an herbicide program that applicators implement and farmers evaluate. If an herbicide application fails to control the targeted weed community sufficiently, farmers can request and may receive a follow-up application (hereafter "respray"), provided labeling restrictions allow for repeated applications within the specific time frame. Despite the implications of resprays on the spread of herbicide-resistant weeds, including weeds resistant to glyphosate (Neve 2008), respray request frequencies and causal factors are poorly understood.

Ideally, decisions to implement weed control are founded on the potential for reduced economic returns considering the weed species composition, abundance, and growth stage relative to the crop (Coble and Mortensen 1992; Cousens 1987). However, in practice, weed control decisions also incorporate both personal and societal standards regarding acceptable infestation levels (Binns et al. 2000; Czapar et al. 1997). Because of these different motivations, the identification of factors that influence management decisions requires research techniques that systematically investigate farmer concerns to uncover those that are held by a majority within a particular farming community. Along these lines, direct-mail surveys have been used to identify problematic weed species (Gibson et al. 2005, 2006), to elucidate usage rates for specific weed management practices (Czapar et al. 1995; Hammond et al. 2006), and to determine farmer attitudes toward weed management concepts (Czapar et al. 1997; Johnson and Gibson 2006). Farmer philosophies on weed management also have been clarified with one-on-one interviews (Johnson et al. 2009; Wilson et al. 2008, 2009). Although direct-mail surveys and interviews have made clear the general beliefs that underlie weed control decisions, still unknown are the specific criteria that perhaps ultimately determine whether control is implemented or withheld because surveys and interviews can occur much later in the season, and therefore, they may fail to incorporate the actual conditions seen by farmers during deliberation. Such disconnections between settings of commercial crop production and scientific inquiry have long been recognized (Thompson and Thompson 1990; Wuest et al. 1999), and have recently been accounted for with paired surveys of weed communities and management practices on cooperator farms (Davis et al. 2009; Luschei et al. 2009).

In this investigation, occurrences and causal factors of glyphosate respray were studied in Illinois by a two-part survey that addressed the following objectives: (1) to determine the relative frequency of respray requests for postemergence glyphosate among custom-applied, glyphosate-resistant soybean fields, and (2) to identify weed community factors associated with glyphosate respray requests. Weed community factors hypothesized to correlate with respray requests included the presence of weed species previously noted as problematic in direct-mail surveys and one-on-one interviews (Gibson et al. 2005, 2006; Kruger et al. 2009), comparatively high weed densities across the entire field, an abundance of weeds visible from roadsides, patches characterized by high weed densities, and evidence of custom application failure. Once weed community factors associated with glyphosate respray requests were identified, a meta-analysis employing published studies on soybean yield reduction in response to increasing weed density was utilized to project impacts of respray-request–driving weed communities in both respray-requested and nonrequested fields.

Materials and Methods

Survey Design. At the beginning of the 2005 and 2006 summer growing seasons, custom applicators were asked to provide logistical information for fields where they administered a single, postemergence application of glyphosate (using label rates and standard commercial formulations) to glyphosate-resistant soybeans. From these registries, subsets of fields were randomly selected for sampling. In 2005, 75% of locations provided by custom applicators were randomly selected, producing a survey comprised of 43 fields; 15 fields managed by 8 farmers in west/southwest Illinois (Cass County) and 28 fields managed by 27 farmers in east Illinois (Iroquois County). In 2006, 80% of locations provided by custom applicators were randomly selected, producing a survey comprised of 90 fields—30 fields managed by 16 farmers in west/southwest Illinois (Cass County), 30 fields managed by 7 farmers in east/southeast Illinois (Effingham County), and 30 fields managed by 22 farmers in east Illinois (Iroquois County). No field was surveyed in both 2005 and 2006, but six farmers were included in both years. The discrepancy between years in the number of fields sampled was primarily because of an additional custom applicator collaborator in 2006. For the 2005 survey, field size averaged 25.19 ± 1.91 (standard error [SE]) ha, and, for the 2006 survey, field size averaged 37.87 ± 2.82 ha. All surveyed fields were seeded with full-season soybean varieties in rows spaced 76 cm apart during May of the respective year. Crop establishment periods (May 1 through June 30) featured normal air temperatures and below-normal rainfall, with rainfall especially low in 2005 (Table 1).

Surveys were conducted 14 d after custom glyphosate applications The species composition and abundance of four types of weed communities were recorded: (1) walk-through communities, (2) drive-by communities, (3) patch communities, and (4) skip communities. Walk-through communities

Table 1. Cumulative growing degree days (GDD) and total precipitation from May 1 to June 30 for counties in which surveys were conducted.

County	District[a]	GDD[b]		Precipitation	
		2005	2006	2005	2006
				—————— cm ——————		
Cass	W/SW	608.7	578.6	5.74	21.66
Effingham	E/SE	–[c]	591.9	–	11.94
Iroquois	E	574.8	514.4	10.31	15.37
Average		592.3	561.6	8.03	16.32
30-yr average[d]		563.9		22.76	

[a] Agricultural district of Illinois as defined by the USDA National Agricultural Statistics Service.

[b] GDD = 0.5(daily maximum temperature – 10) + 0.5(daily minimum temperature – 10), where temperatures are Celsius (C), minimum temperatures are not permitted to fall below 10 C, and maximum temperatures are not permitted to exceed 30 C. Temperature data were provided by the National Oceanic and Atmospheric Administration–National Climate Data Center (NOAA-NCDC 2009).

[c] The survey was not conducted in Effingham County during 2005.

[d] Average GDD and precipitation for Cass, Effingham, and Iroquois counties from 1974 to 2004.

were all weeds within 10 quadrats (1 m^2) that were positioned by walking two transects, one parallel and one perpendicular to crop rows, of random-number pace lengths, with pace lengths rerandomized for each site. Drive-by communities were only weeds taller than the crop canopy in ten transects (0.1 m wide, 100 long) starting 20 m from roadsides and running parallel to randomly selected crop rows, with crop rows rerandomized for each site. Patch communities comprised all weeds within 1-m^2 quadrats centrally positioned in irregularly shaped areas distinguished by high weed densities relative to the overall weed density for that field (1 quadrat/patch). Skip communities comprised all weeds within 1-m^2 quadrats centrally positioned in rectangular areas of exceptionally high weed density for that field (1 quadrat/skip).

The rationale behind the four weed communities of this survey was to collect information on both actual infestation severity and factors related to human perception of infestation severity. Drive-by communities were visible from field edges or from moving automobiles, and thus represented cursory inspections of weed infestations. In contrast, walk-through communities were discernible only by entering fields, and thus represented more thorough inspections of weed infestations. Patches were consequences of natural, large seedling recruitment events. Skips were results of custom applicator error. Incidences of patches and skips were discernible from the field edges, but trips into fields were necessary to determine the densities and compositions of both patch and skip communities.

For all communities, only weeds thought to have been present at the time of custom application were counted. This was accomplished by counting only surviving weeds that were at least similar in size and developmental stage to the standing remains of weeds killed by glyphosate, as determined from visible inspection. Newly emerged seedlings, which were thought to have emerged after glyphosate application, were not counted.

In addition to weed species composition and abundance, further data were collected, including (1) patch area, the

elliptical area of each patch determined with measurements of radii at maximum length and width; (2) skip area, the rectangular area of each skip determined with measurements of length and width; and (3) incidence of glyphosate respray request, determined by querying custom applicators at the conclusion of the growing season. Based on observations of weed survivorship in 2005, the efficacy of custom application was hypothesized to be inversely proportional to weed density at the time of custom application (Dieleman et al. 1999; Taylor and Hartzler 2000). To test this hypothesis, the weed population density at the time of custom application was determined for each site in 2006 (90 sites) by counting both viable and dead weeds within 10 randomly placed 1-m^2 quadrats. Although standing remains of weeds killed by glyphosate were clearly visible, weed population densities at the time of custom application may have been underestimated because small seedlings treated with glyphosate may have been difficult to detect at the time the survey was conducted (14 d after application).

Statistical Analysis. Multiple logistic regression (Hosmer and Lemeshow 2000) was used to identify the weed community factors most predictive of the binary outcome variable "respray request." The modified Levene's test (Neter et al. 1996) indicated inequality in error variance between 2005 and 2006, and therefore, data were analyzed separately by year. Multiple logistic regression models with terms for population densities of the various weed communities (both summed across species and within species) and indicator variables for presence/absence of skips and patches, were fitted using maximum-likelihood estimators with the LOGIT subroutine of SYSTAT 11.0.1.[1] A global model containing all variables and submodels thereof were compared for goodness of fit and parsimony with the use of Akaike's Information Criterion (AIC$_c$) modified for small sample sizes (ratio of observations to number of model parameters < 40) (Burnham and Anderson 2002). Relative likelihood of candidate models was assessed by calculating Akaike weights (w_i) in relation to the model that minimized AIC$_c$ (Burnham and Anderson 2002). Odds ratios, with 95% confidence intervals, were reported for variables within the most parsimonious models for 2005 and 2006 (Hosmer and Lemeshow 2000). Population densities of weed community factors most associated with respray request were compared between respray-requested and nonrequested fields with bootstrapped means and standard deviations calculated with the use of the STATS subroutine of SYSTAT 11.0.1.

Logistic regression was also used to test the hypothesis that glyphosate efficacy decreased as weed densities at the time of custom application increased. Using counts of viable and dead weeds collected in 2006, the binary outcome variable "survival" was modeled in response to weed population density at the time of custom application with the use of the LOGIT subroutine of SYSTAT 11.0.1.

Meta-Analysis to Project Impacts of Weed Community Characteristics Highly Associated with Respray Requests. A systematic search for publications was conducted with the use of Web of Science® (from 1955) and Biological Abstracts® (from 1926). Search strategies used subject headings and key
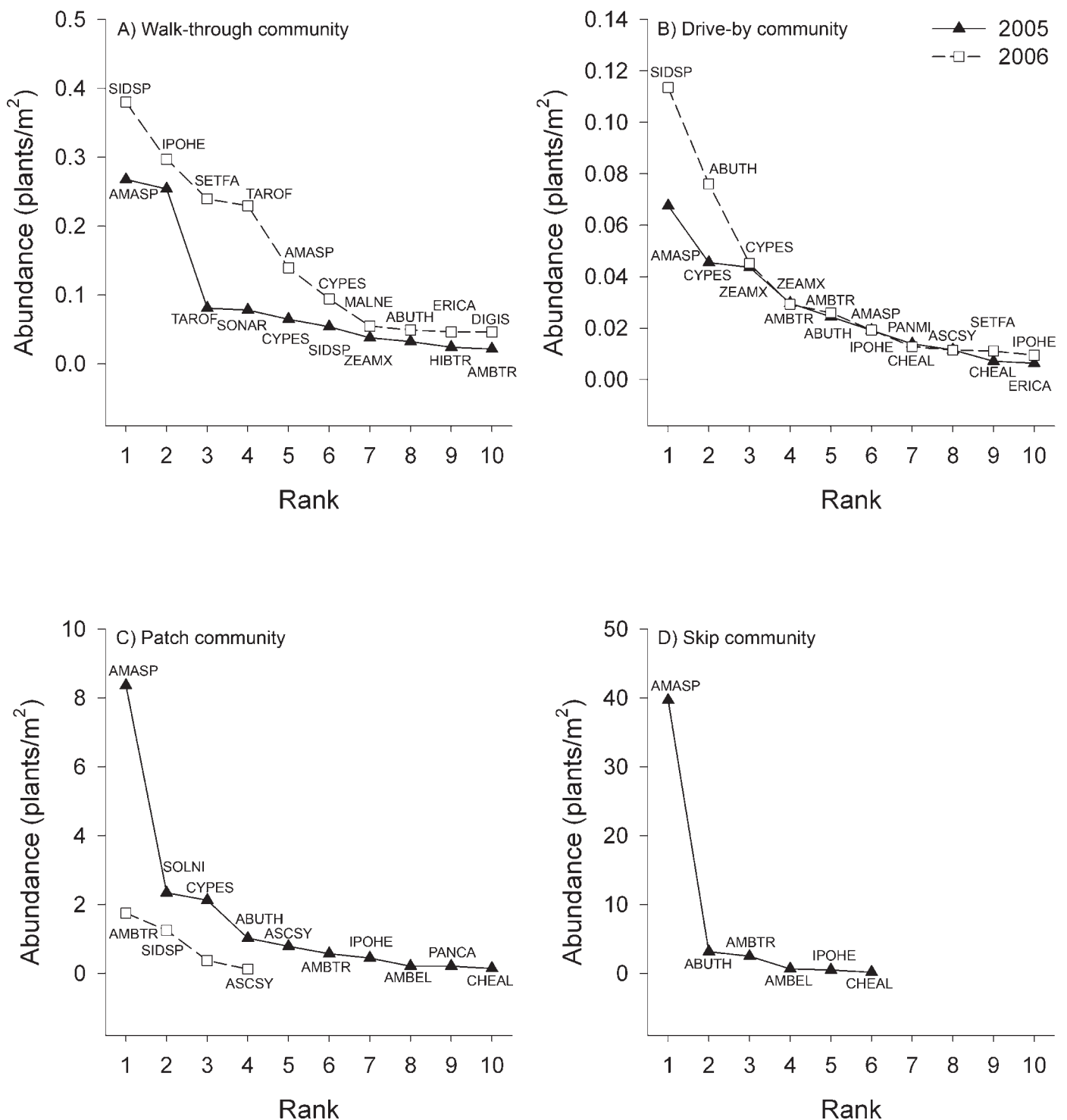
Figure 1. Rank-abundance curves for the 10 most abundant species of (a) walk-through, (b) drive-by, (c) patch, and (d) skip weed communities of custom-applied, glyphosate-resistant soybean fields surveyed 14 d after postemergence applications of glyphosate. Data points represent population density means. Only one species label is provided where ranks are consistent across years. Explanation of Bayer codes: ABUTH = velvetleaf, AMASP = *Amaranthus* spp., AMBEL = common ragweed, AMBTR = giant ragweed, ASCSY = common milkweed (*Asclepias syriaca* L.), CHEAL = common lambsquarters, CYPES = yellow nutsedge, DIGIS = smooth crabgrass (*Digitaria ischaemum* Schreb. ex Muhl), ERICA = horseweed, HIBTR = Venice mallow (*Hibiscus trionum* L.), IPOHE = ivyleaf morningglory, MALNE = common mallow (*Malva neglecta* Wallr.), PANCA = witchgrass (*Panicum capillare* L.), PANMI = wild-proso millet (*Panicum miliaceum* L.), SETFA = giant foxtail, SIDSP = prickly sida, SOLNI = black nightshade (*Solanum nigrum* L.), SONAR = perennial sowthistle (*Sonchus arvensis* L.), TAROF = dandelion, ZEAMX = corn.

Table 2. Maximum-likelihood selection criteria for candidate models describing the binary outcome variable "respray request" in response to weed community factors for custom-applied soybean fields in Illinois in 2005.

ID	Model[a]	$\log(L)$[b]	K	AIC_c	Δ_i	w_i
1	n_{all}, l, s, p	−40.6	11	111.7	82.0	1.1×10^{-18}
2	n_d, n_w, n_p, n_s	−13.8	4	36.7	6.9	0.021
3	n_d, n_w, n_s	−14.4	3	35.4	5.7	0.039
4	n_d, n_w, n_p	−13.9	3	34.4	4.7	0.065
5	n_w, n_p, n_s	−16.9	3	40.4	10.7	0.003
6	n_d, n_p, n_s	−13.8	3	34.2	4.5	0.072
7	n_d, n_s	−14.4	2	33.1	3.4	0.125
8	n_d, n_p	−13.9	2	32.1	2.4	0.207
9	n_d, n_w	−14.8	2	33.9	4.2	0.084
10	n_p, n_s	−16.9	2	38.1	8.4	0.010
11	n_w, n_s	−17.3	2	38.9	9.2	0.007
12	n_w, n_p	−16.9	2	38.1	8.4	0.010
13	n_d	−14.8	1	31.7	1.9	0.252
14	n_s	−17.4	1	36.9	7.2	0.019
15	n_w	−17.4	1	36.9	7.2	0.019
16	n_p	−16.9	1	35.9	6.2	0.031
17	l	−16.8	1	35.7	6.0	0.034
18	s	−14.6	1	31.3	1.6	0.309
19	p	−16.8	1	35.7	6.0	0.034
20	n_d, s[c]	−12.7	2	29.7	0	0.687

[a] Explanation of abbreviations for independent variables: n_{all} = population density of all four weed communities (drive by, walk through, patch, and skip) included in model; n_d, n_w, n_p, n_s = population density of weeds in drive-by, walk-through, patch, and skip communities, respectively, summed over species; l = county location of field; s = presence/absence of skip; p = presence/absence of patch.

[b] Explanation of model selection criteria abbreviations: $\log(L)$ = log-likelihood from maximum-likelihood fit of logistic regression model with respray request incidence as the dependent variable and predictor variables indicated in the "Model" column; K = number of predictor variables within model; AIC_c = Akaike's Information Criterion, adjusted for small sample size (ratio observation/K < 40); Δ_i = Akaike differences, the difference between a given model and the model that minimizes AIC_c; w_i = Akaike weights, the relative likelihood of a model, given a set of candidate models.

[c] The most parsimonious model (Model 20) provided a better fit to the data than the intercept-only model (likelihood ratio test, χ^2 = 9.33, df = 2, P < 0.01).

words with language restricted to English. To be included in the analysis, a published study had to meet the following criteria: (1) determine the influence of weed density on crop yield reduction for full-season soybean varieties seeded in rows spaced 76 cm, (2) measure season-long interference for weed species associated with respray requests, and (3) employ an additive experimental design (Harper 1977). Six studies met the inclusion criteria. Functions for soybean yield loss in response to increasing weed density either were taken directly from published studies or were derived from published data by fitting hyperbolic functions with least squares, iterative procedures using the NONLIN subroutine of SYSTAT 11.0.1. The impacts of implementing or withholding glyphosate resprays, as perceived by farmers primarily concerned with crop yield, were estimated by superimposing population densities of respray-request–driving weed communities onto soybean yield loss functions.

Results and Discussion

Weed Communities. Fourteen days after custom applications of postemergence glyphosate, surviving weeds were commonplace among the surveyed soybean fields. For walk-through communities, population densities averaged 1.1 ± 0.1 (SE) weeds/m^{-2} in 2005, and 1.8 ± 0.3 weeds/m^{-2} in 2006. Species that were abundant in walk-through communities in both 2005 and 2006 were *Amaranthus* spp. (a complex of three difficult-to-distinguish species including common waterhemp, redroot pigweed [*Amaranthus retroflexus* L.], and smooth pigweed [*Amaranthus hybridus* L.]), dandelion

(*Taraxacum officinale* Weber in Wiggers), ivyleaf morningglory [*Ipomoea hederacea* (L.) Jacq.], prickly sida (*Sida spinosa* L.), velvetleaf (*Abutilon theophrasti* Medicus), and yellow nutsedge (*Cyperus esculentus* L.) (Figure 1a). Despite similarities in species composition, yearly walk-through communities were distinct because of interannual variation of relative species abundance. In 2005, walk-through communities were dominated by *Amaranthus* spp. and ivyleaf morningglory, whereas in 2006, prickly sida, ivyleaf morningglory, giant foxtail (*Setaria faberi* Herrm.) and dandelion were dominant. Because no field was surveyed in both 2005 and 2006, interannual variation of dominant weed species perhaps reflected differences in seedbank floras caused by dissimilar management and invasion histories. Also, dominant species differences between years may have been evidence of the combined effects of temporal emergence patterns within weed communities and variation in crop production schedules among farms and years.

Drive-by communities occurred in 88% of surveyed fields in 2005, and 60% of surveyed fields in 2006. Where present, drive-by communities averaged 2.9 ± 1.9 weeds m^{-2} in 2005, 3.7 ± 1.9 weeds m^{-2} in 2006. *Amaranthus* spp., yellow nutsedge, and volunteer corn (*Zea mays* L.) dominated drive-by communities in 2005, and in 2006, prickly sida and velvetleaf were dominant (Figure 1b). Across all surveyed fields and for several species, population densities of drive-by communities were significantly correlated (α = 0.05) with population densities of walk-through communities. In 2005 (n = 43), such species included: *Amaranthus* spp. (r = 0.58, P < 0.01), common lambsquarters (*Chenopodium album* L.)
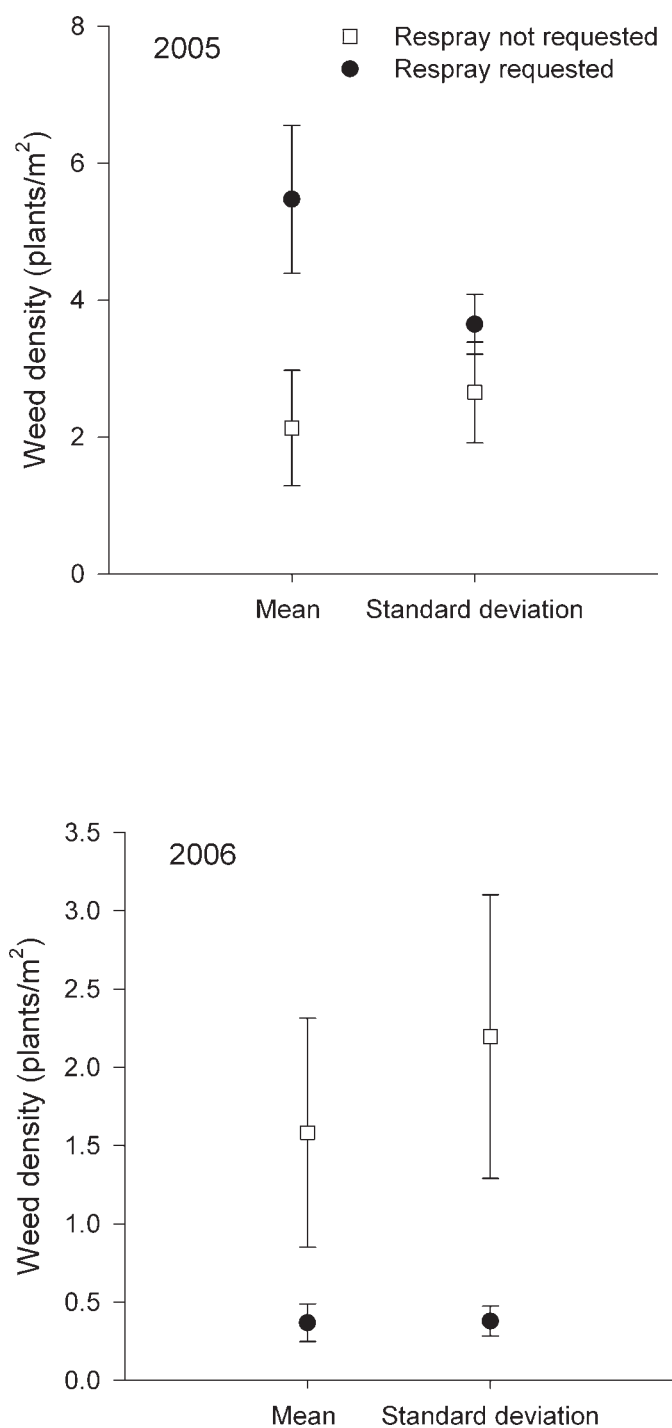
Figure 2. Bootstrap estimated means and standard deviations for densities of weed communities most associated with respray requests. Data represent means with 95% confidence intervals.

($r = 0.68$, P $<$ 0.01), common ragweed (*Ambrosia artemisiifolia* L.) ($r = 0.66$, P $<$ 0.01), and ivyleaf morningglory ($r = 0.33$, P $<$ 0.05); and, in 2006 ($N = 90$) included: *Amaranthus* spp. ($r = 0.67$, P $<$ 0.01), common lambsquarters ($r = 0.94$, P $<$ 0.001), giant ragweed (*Ambrosia trifida* L.) ($r = 0.62$, P $<$ 0.01), prickly sida ($r = 0.81$, P $<$ 0.001), and velvetleaf ($r = 0.63$, P $<$ 0.01).

Compared to the drive-by community, the walk-through community was considered more representative of the "true" weed community for a particular field because the walk-through community included weeds throughout the field that were both taller and shorter than the crop canopy, whereas the drive-by community included only weeds taller than the crop canopy and located near the roadside. Significant correlations between walk-through and drive-by population densities suggest that, for several weed species common to soybean fields of Illinois, whole-field densities can be accurately determined with roadside surveys, a widely used scouting technique among soybean growers in this region (Czapar et al. 1995).

Weed patches occurred in 44% of surveyed fields in 2005 and in 7% of surveyed fields in 2006. In fields with patches present, the number of patches per field averaged 2.5 ± 0.5 in 2005 and 1.3 ± 0.2 in 2006. Patch area relative to total field area (patch coverage) differed substantially among patches, with individual patches covering 0.001% to 14.8% of fields in which they occurred. However, in general, patches were relatively small, with median patch coverage equal to 0.04% in 2005 and 0.05% in 2006. In 2005, central tendency in patch weed community population density was best indicated by the mode, which equaled 3 weeds/m^{-2}. In 2006, patch community densities were symmetrically distributed around the mean, which equaled 3.5 ± 1.2 weeds/m^{-2}. In 2005, patch communities were dominated by *Amaranthus* spp., whereas in 2006, giant ragweed and prickly sida were dominant (Figure 1c).

Skips were present in 11.6% of surveyed fields in 2005 but were absent from surveyed fields in 2006. Among fields with skips, the number of skips per field averaged 1.4 ± 0.3, with individual skips covering 0.001 to 0.7% of fields in which they occurred. Median percent coverage per skip equaled 0.01%. Weed communities within skips consisted of six species, with *Amaranthus* spp. dominant (Figure 1d).

The presence of weeds surviving glyphosate is consistent with previous research indicating that certain weed species exhibit inherent tolerance or resistance to label rates of glyphosate (Heap 2009; Knezevic et al. 2009; Westhoven et al. 2008). Also, surviving weeds may have resulted from decreased glyphosate efficacy associated with increased weed density (Dieleman et al. 1999; Taylor and Hartzler 2000). For every additional weed/m^{-2} present at the time of custom application in 2006, the probability of survival increased 0.90% (odds ratio for "survivorship" [coded as: survive = 1, not survive = 0] in response to "weed population density at the time of custom application" = 1.009, 95% confidence interval [CI] = 1.004 to 1.014). Regardless of the basis for survival, the prevalence of weeds in custom-applied, glyphosate-resistant soybean fields points toward the need for integrated weed management (IWM) tactics that reduce weed population densities both before and after postemergence applications of glyphosate.

Glyphosate Respray Requests. Relative frequencies of glyphosate respray requests were consistent across years, with resprays ordered for 14.0% of surveyed fields in 2005 and 14.4% of surveyed fields in 2006. In 2005, relative frequencies of respray requests were similar across counties

Table 3. Maximum-likelihood selection criteria for candidate models describing the binary outcome variable "respray request" in response to weed community factors for custom-applied soybean fields in Illinois in 2006.

ID	Model[a]	log(L)[b]	K	AIC$_c$	Δ_i	w_i
1	n_{all}, l, p	−28.3	9	80.1	15.6	1.9×10^{-4}
2	n_d, n_w, n_p	−32.9	3	72.4	7.9	0.009
3	n_d, n_w	−33.7	2	71.7	7.2	0.012
4	n_w, n_p	−32.9	2	70.1	5.6	0.028
5	n_d, n_p	−36.2	2	76.7	12.2	0.001
6	n_p, n_w	−32.9	2	70.1	5.6	0.028
7	n_d	−36.9	1	75.9	11.4	0.002
8	n_w	−33.7	1	69.5	5.0	0.038
9	n_p	−36.2	1	74.5	10.0	0.003
10	l	−31.3	1	64.7	0.2	0.416
11	p	−36.2	1	74.5	10.0	0.003
12	n_w, l[c]	−30.1	2	64.5	0	0.459

[a] Explanation of abbreviations for independent variables: n_{all} = population density of three survey classes (drive by, walk through, patch) included in model; n_d, n_w, n_p, = population density of weeds in drive-by, walk-through, and patch communities, respectively, summed over species; l = county location of field; P = presence/absence of patch.

[b] Explanation of model selection criteria abbreviations: log(L) = log-likelihood from maximum-likelihood fit of logistic regression model with respray request incidence as the dependent variable and predictor variables indicated in the "Model" column; K = number of predictor variables within model; AIC$_c$ = Akaike's Information Criterion, adjusted for small sample size (ratio observation/K < 40); Δ_i = Akaike differences, the difference between a given model and the model that minimizes AIC$_c$; w_i = Akaike weights, the relative likelihood of a model, given a set of candidate models.

[c] The most parsimonious model (Model 12) provided a better fit to the data than the intercept-only model (likelihood ratio test, χ^2 = 13.93, df = 2, P < 0.001).

(χ^2 = 1.019, df = 1, P = 0.31), with resprays requested for 6.7% of surveyed fields in Cass County, and 17.9% of surveyed fields in Iroquois County. However, in 2006, relative frequencies of respray requests varied among counties (χ^2 = 7.732, df = 2, P = 0.02), with resprays requested for 20% of surveyed fields in Cass County, 0% of surveyed fields in Effingham County, and 23% of surveyed fields in Iroquois County.

To our knowledge, these results represent first reports on respray request rates for custom-applied fields. Respray request rates from this investigation, combined with previous reports indicating that approximately 45% of herbicide applications to soybean fields across Illinois are administered by custom applicators (USDA-NCIPMC 2000), suggest that a significant percent of soybean fields in Illinois are resprayed annually because of farmer dissatisfaction with custom applications.

Weed Community Factors Associated with Respray Requests. In 2005, respray requests were associated with both population densities of drive-by weed communities and the presence of skips (Table 2). As indicated by the odds ratio derived from the most parsimonious regression model, a skip within a field increased the odds of respray request by a multiplicative factor of 9.53 (odds ratio for "respray request" [coded as: requested = 1, not requested = 0] in response to "skip" [coded as: present = 1, absent = 0] = 9.53, 95% CI = 1.09 to 83.13). Although the odds ratio for "respray request" in response to "population density of drive-by weed community" was not statistically significant (odds ratio = 1.03, 95% CI = 0.99 to 1.06), population densities of drive-by weed communities were, on average, 2.5 times greater in respray-requested fields compared to nonrequested fields (Figure 2).

In 2006, respray requests were highly associated with population densities of walk-through weed communities (Table 3). The probability of a respray request increased as

population densities of walk-through communities decreased, as indicated by both the odds ratio derived from the most parsimonious logistic regression model (odds ratio for "respray request" [coded as: requested = 1, not requested = 0] in response to "walk-through community density" = 0.90, 95% CI = 0.81 to 0.99) and comparisons of population density means (Figure 2). In addition, respray-requested fields were characterized by reduced variance in weed community population density compared to nonrequested fields. Together, these results suggested a population of farmers in 2006 with both a low tolerance for weeds and a tendency to demand action from custom applicators. Such low-tolerance, action-demanding farmers may not have been detected in 2005 because either they were excluded from the sample population or because a critical distinguishing condition (low weed population density) was absent. Also, it should be noted that factors external to weed communities, including herbicide performance guarantees, were not included in this analysis. Accordingly, respray decisions may have involved factors other than the weed community factors described in this investigation.

For both 2005 and 2006, logistic regression models with terms for population densities of individual species featured increased AIC$_c$ (indicating lower parsimony) compared to logistic regression models with terms for population densities summed across species (data not shown). Thus, respray requests were not motivated by particular weed species, but by the perceived impacts of all species present in respray-driving weed communities.

Projected Impacts of Respray-Driving Weed Communities. Predicting the impact of residual weed communities comprised of multiple species is difficult because mixtures of weeds may reduce crop yield to a lesser degree than the sum of their independent actions (Blackshaw et al. 1987; Toler et al. 1996) and weeds surviving herbicides can be less competitive than nonexposed weeds (Schmenk and Kells 1998). None-
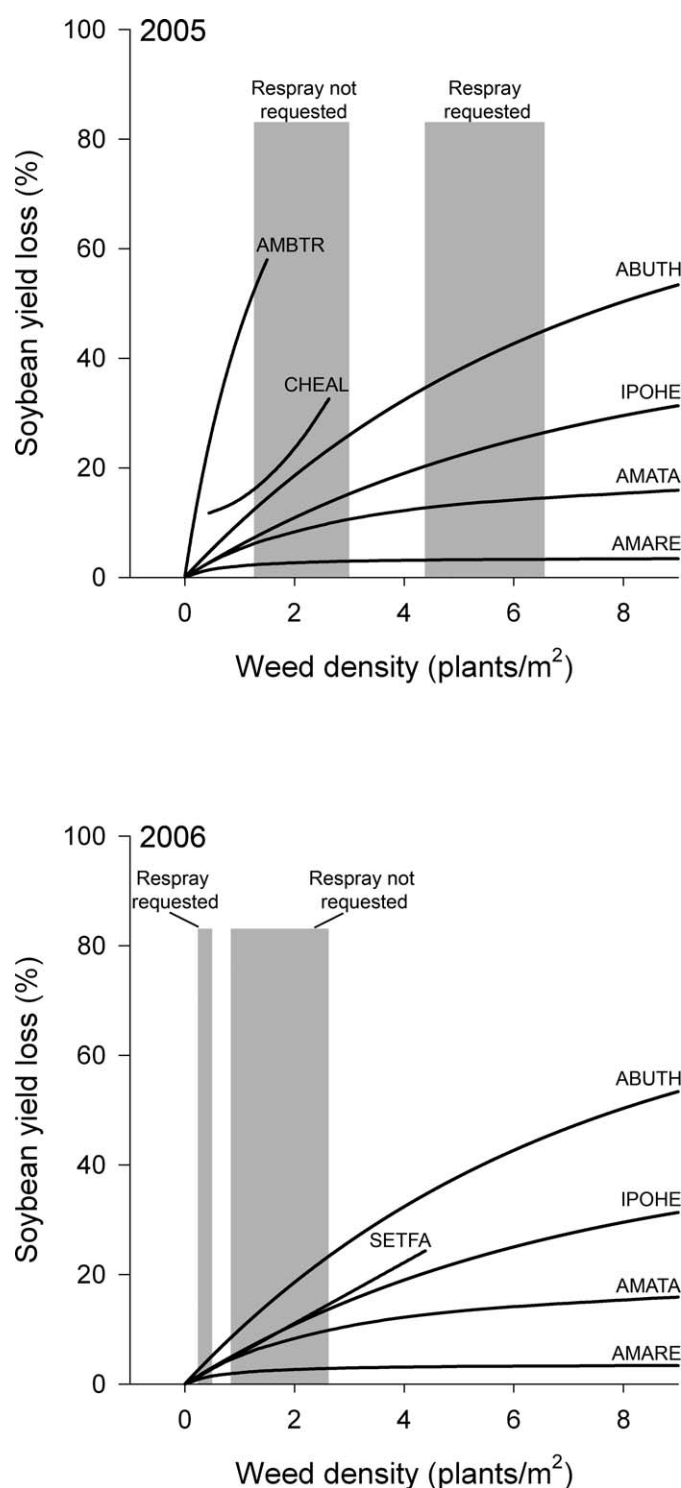
theless, previous experiments that studied soybean yield loss in response to increasing densities of a single weed species were utilized to gain insight into maximum yield loss potentials from weed communities observed in this investigation (Figure 3). These studies indicate that, for respray-requested fields in 2005, substantial yield loss may have occurred if weeds were not removed, and thus, for these fields, respray requests were warranted. Also, substantial yield loss was likely in nonrequested fields in 2005, suggesting that farmers failed to recognize the threat posed by weed communities present in soybean fields after postemergence glyphosate applications. Failure to recognize weed interference potentials also occurred in 2006 as weed communities capable of causing substantial yield loss were again present in nonrequested fields. For respray-requested fields in 2006, weed communities were projected to have little impact on crop yield, and thus, these respray requests may have represented preemptive control tactics ordered by farmers concerned with weed seedbank return. Also, respray requests in 2006 may have reflected concerns for aesthetics or landlord demands (Czapar et al., 1997).

Potential Application of Results. The prevalence of yield-damaging weed communities in custom-applied, glyphosate-resistant soybean fields and the potential long-term benefits of eliminating weeds that survive glyphosate strongly suggest a need for additional weed control tactics that are implemented after postemergence applications of glyphosate. When implementing these control tactics, farmers and custom applicators should incorporate appropriate IWM practices to reduce the spread of glyphosate-resistant weeds. Accordingly, custom applicators should administer resprays with tank mixes of postemergence herbicides with different modes of action (Knezevic et al. 2009; Neve 2008). Moreover, custom applicators may be able to prevent both weed escapes and respray requests by avoiding skips and recommending IWM tactics that suppress weeds prior to postemergence applications of glyphosate. Such tactics include, but are not limited to, use of soil-residual herbicides (Westhoven et al. 2008), increased soybean seeding rate (Arce et al. 2009) and decreased soybean row spacings (Harder et al. 2007). To ensure that custom applicators are familiar with these management tactics and aware of their role in preserving glyphosate's utility in soybean production, IWM education programs should be directed toward custom application services.

Sources of Materials

Acknowledgments

Figure 3. Percent yield loss of soybean in response to increasing weed densities of species common to weed communities highly associated with respray requests. Yield loss functions for season-long interference were obtained from literature sources and covered only densities actually used in model development. Shaded areas represent 95% confidence intervals of bootstrap mean densities for weed communities associated with respray requests. Explanation of Bayer codes: ABUTH = velvetleaf, AMARE = redroot pigweed, AMATA = common waterhemp, AMBTR = giant ragweed, CHEAL = common lambsquarters, IPOHE = ivyleaf morningglory, SETFA = giant foxtail. Figure adapted from Stoller et al. (1987) and based on the following studies: Bensch et al. (2003), Dekker and Meggitt (1983), Harrsion (1990), Harrison et al. (1985), Holloway and Shaw (1996), and Webster et al. (1994).

Literature Cited

Arce, G. D., P. Pedersen, and R. G. Hartzler. 2009. Soybean seeding rate effects on weed management. Weed Technol. 23:17–22.

Bensch, C. N., M. J. Horak, and D. Peterson. 2003. Interference of redroot pigweed (*Amaranthus retroflexus*), Palmer amaranth (*A. palmeri*), and common waterhemp (*A. rudis*) in soybean. Weed Sci. 51:37–43.

Binns, M. R., J. P. Nyrop, and W. van der Werf. 2000. Sampling and Monitoring in Crop Protection. New York, NY: CABI. 284 p.

Blackshaw, R. E., G. W. Anderson, and J. Dekker. 1987. Interference of *Sinapis arvensis* L. and *Chenopodium album* L. in spring rapeseed (*Brassica napus* L.). Weed Res. 27:207–213.

Burnham, K. P. and D. R. Anderson. 2002. Model Selection and Inference: A Practical Information-Theoretic Approach. 2nd ed. New York, NY: Springer Verlag. 496 p.

Coble, H. D. and D. A. Mortensen. 1992. The threshold concept and its application to weed science. Weed Technol. 6:191–195.

Cousens, R. 1987. Theory and reality of weed control thresholds. Plant Prot. Q. 2:13–20.

Czapar, G. F., M. P. Curry, and M. E. Gray. 1995. Survey of integrated pest management practices in central Illinois. J. Prod. Agric. 8:483–486.

Czapar, G. F., M. P. Curry, and L. M. Wax. 1997. Grower acceptance of economic thresholds for weed management in Illinois. Weed Technol. 11:828–831.

Davis, V. M., K. D. Gibson, V. A. Mock, and W. G. Johnson. 2009. In-field and soil-related factors that affect the presence and prediction of glyphosate-resistant horseweed (*Conyza canadensis*) populations collected from Indiana soybean fields. Weed Sci. 57:281–289.

Dekker, J. and W. F. Meggitt. 1983. Interference between velvetleaf (*Abutilon theophrasti* Medic.) and soybean (*Glycine max* (L.) Merr.). 2. Population dynamics. Weed Res. 23:103–107.

Dieleman, J. A., D. A. Mortensen, and A. R. Martin. 1999. Influence of velvetleaf (*Abutilon theophrasti*) and common sunflower (*Helianthus annuus*) density variation on weed management outcomes. Weed Sci. 47:81–89.

Gibson, K. D., W. G. Johnson, and D. E. Hillger. 2005. Farmer perceptions of problematic corn and soybean weeds in Indiana. Weed Technol. 19:1065–1070.

Gibson, K. D., W. G. Johnson, and D. E. Hillger. 2006. Farmer perceptions of weed problems in corn and soybean rotation systems. Weed Technol. 20:751–755.

Hammond, C. M., E. C. Luschei, C. M. Boerboom, and P. J. Nowak. 2006. Adoption of integrated pest management tactics by Wisconsin farmers. Weed Technol. 20:756–767.

Harder, D. B., C. L. Sprague, and K. A. Renner. 2007. Effect of soybean row width and population on weeds, crop yield, and economic return. Weed Technol. 21:744–752.

Harper, J. L. 1977. Population Biology of Plants. New York, NY: Academic Press. 892 p.

Harrison, S. K. 1990. Interference and seed production by common lambsquarters (*Chenopodium album*) in soybeans (*Glycine max*). Weed Sci. 38:113–118.

Harrison, S. K., C. S. Williams, and L. M. Wax. 1985. Interference and control of giant foxtail (*Setaria faberi*) in soybeans (*Glycine max*). Weed Sci. 33:203–208.

Heap, I. 2009. The International Survey of Herbicide Resistant Weeds. www.weedscience.com. Accessed: May 25, 2010.

Holloway, J. C. and D. R. Shaw. 1996. Effect of herbicides on ivyleaf morningglory (*Ipomoea hederacea*) interference in soybean (*Glycine max*). Weed Sci. 44:860–864.

Hosmer, D. W. and S. Lemeshow. 2000. Applied Logistic Regression. 2nd ed. New York, NY: Wiley. 375 p.

Johnson, W. G. and K. D. Gibson. 2006. Glyphosate-resistant weeds and resistance management strategies: An Indiana grower perspective. Weed Technol. 20:768–772.

Johnson, W. G., M.D.K. Owen, G. R. Kruger, B. G. Young, D. R. Shaw, R. G. Wilson, J. W. Wilcut, D. L. Jordan, and S. C. Weller. 2009. U.S. farmer awareness of glyphosate-resistant weeds and resistance management strategies. Weed Technol. 23:308–312.

Knezevic, S. Z., A. Darta, J. Scott, R. N. Klein, and J. Golus. 2009. Problem weed control in glyphosate-resistant soybean with glyphosate tank mixes and soil-applied herbicides. Weed Technol. 23:507–512.

Kruger, G. R., W. G. Johnson, S. C. Weller, M.D.K. Owen, D. R. Shaw, J. W. Wilcut, D. L. Jordan, R. G. Wilson, M. L. Bernards, and B. G. Young. 2009. U.S. grower views on problematic weeds and changes in weed pressure in glyphosate-resistant corn, cotton, and soybean cropping systems. Weed Technol. 23:162–166.

Luschei, E. C., C. M. Hammond, C. M. Boerboom, and P. J. Nowak. 2009. Convenience sample of on-farm research cooperators representative of Wisconsin farmers. Weed Technol. 23:300–307.

Neter, J., M. H. Kutner, C. J. Nachtsheim, and W. Wasserman. 1996. Applied Linear Statistical Models. Chicago, IL: Irwin. 1408 p.

Neve, P. 2008. Simulation modelling to understand the evolution and management of glyphosate resistance in weeds. Pest Manag. Sci. 64:392–401.

[NOAA-NCDC] National Oceanic and Atmospheric Administration—National Climate Data Center. 2009. Annual Climatological Summaries. http://www.ncdc.noaa.gov/oa/climate/stationlocator.html. Accessed: May 25, 2010.

Schmenk, R. and J. J. Kells. 1998. Effects of soil-applied atrazine and pendimethalin on velvetleaf (*Abutilon theophrasti*) competiveness in corn. Weed Technol. 12:47–52.

Stoller, E. W., S. K. Harrison, L. M. Wax, E. E. Regnier, and E. D. Nafziger. 1987. Weed interference in soybeans (*Glycine max*). Rev. Weed Sci. 3:155–181.

Taylor, K. L. and R. G. Hartzler. 2000. Effect of seed bank augmentation on herbicide efficacy. Weed Technol. 14:261–267.

Toler, J. E., J. B. Guice, and E. C. Murdock. 1996. Interference between johnsongrass (*Sorghum halepense*), smooth pigweed (*Amaranthus hybridus*), and soybean (*Glycine max*). Weed Sci. 44:331–338.

Thompson, R. and S. Thompson. 1990. The on-farm research program of Practical Farmers of Iowa. Am. J. Altern. Agr. 5:163–167.

[USDA-NASS] U.S. Department of Agriculture–National Agricultural Statistics Service. 2009. Illinois Farm Report, November 12, 2009, IFR-09-15. http://www.nass.usda.gov/Statistics_by_State/Illinois/Publications/Farm_Reports/2009/ifr0915.pdf. Accessed: May 25, 2010.

[USDA-NCIPMC] U.S. Department of Agriculture–North Central Integrated Pest Management Center. 2000. Crop Profile for Soybean in Illinois. http://www.ipmcenters.org/cropprofiles/docs/ILsoybeans.pdf. Accessed: May 25, 2010.

Webster, T. M., M. M. Loux, E. E. Regnier, and S. K. Harrison. 1994. Giant ragweed (*Ambrosia trifida*) canopy architecture and interference studies in soybean (*Glycine max*). Weed Technol. 8:559–564.

Westhoven, A. M., J. M. Stachler, M. M. Loux, and W. G. Johnson. 2008. Management of glyphosate tolerant common lambsquarters (*Chenopodium album*) in glyphosate-resistant soybean. Weed Technol. 22:628–634.

Wilson, R. S., N. Hooker, M. Tucker, J. LeJeune, and D. Doohan. 2009. Targeting the farmer decision making process: a pathway to increased adoption of integrated weed management. Crop Prot. 28:756–764.

Wilson, R. S., M. A. Tucker, N. H. Hooker, J. T. LeJeune, and D. Doohan. 2008. Perceptions and beliefs about weed management: perspectives of Ohio grain and produce farmers. Weed Technol. 22:339–350.

Wuest, S. B., D. K. McCool, B. C. Miller, and R. J. Veseth. 1999. Development of more effective conservation farming systems through participatory on-farm research. Am. J. Altern. Agr. 14:98–102.